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Solving the Non-Convexity Problem in Some Shopping-Time and Human-Capital Models

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Abstract

Several works in the shopping-time and in the human-capital literature, due to the nonconcavity of the underlying Hamiltonian, use first-order conditions in dynamic optimization to characterize necessity, but not sufficiency, in intertemporal problems. In this work I choose one paper in each one of these two areas and show that optimality can be characterized by means of a simple aplication of Arrow's (1968) sufficiency theorem.

1 Introduction

Several works in the economic literature, particularly in the shopping-time[1] (e.g., Lucas (2000), Gillman, Siklos and Silver (1997), Cysne (2003), Cysne, Monteiro and Maldonado (2004))[2] and in the human-capital literature (e.g. Uzawa (1965), Lucas (1988 and 1990), Chari, Jones and Manuelli (1995),

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[1]As pointed out by Lucas (2000), nonconvexities in the shopping-time literature are related to the fixed costs of converting interest-bearing assets into cash (the costs of going to the bank in Baumol's (1952) analysis).

[2]See equation 5.3 in Lucas (2000), equation (10) in Cysne, Maldonado and Monteiro (2004) and the terms Ac and $(1-A)c$ in the Hamiltonian of Section 2 in Gillman et al. (1997).

Ladron-de-Guevara et al. (1999) and Kosempel (2001))[3] use first-order conditions in dynamic optimization to characterize necessity, but not sufficiency, in intertemporal problems. The reason, always either implicitly or explicitly recognized by the authors, is that the non-concavity of the associated Hamiltonian does not allow for the use of Mangasarian's (1966) well known sufficient conditions in optimum control.

Mangasarian's theorem states that if the Hamiltonian is (strictly) concave with respect to the control and the state variables, then the first-order conditions are also sufficient for an interior (unique) optimum. The papers cited above are some examples in the economic literature in which such conditions are not obeyed.

Arrow's (1968) theorem, though, generalizes Mangasarian's result, and, as we shall see, is able to generate sufficiency in some cases in which Mangasarian's result is not directly applicable. Arrow's theorem requires another type of concavity. In words[4], first, the Hamiltonian is maximized with respect to the control variables, for a given value of the costate variables. The optimum values of the control variables, as a function of the state variables and of the costate variable, are then substituted into the Hamiltonian. Call this new function (of the state and costate variables) the maximized Hamiltonian. Arrow's main result is that if this maximized Hamiltonian is (strictly) concave with respect to the state variable, for the given value of the costate functions, then the first order conditions characterize a (unique, concerning the state variable) optimum[5].

Of course, if the Hamiltonian is concave with respect to both the state and control variables, then the maximized (with respect to the control variables) Hamiltonian will be concave in the state variables. But the reverse is not true. This is the reason why one says that Arrow's theorem generalizes the Mangasarian's sufficient conditions.

The main purpose of this article is calling the attention to the fact, and exemplifying how, in some specific cases, an application of Arrow's theorem can yield returns at very reasonable costs in terms of the required algebrisms. As a by-product of the analysis, a complementary insight into some papers of the shopping-time and human-capital literature (the ones used as examples) is also delivered.

[3]See equation (15) in Uzawa, equation (13) in Lucas (1988), equation (2.3) in Lucas (1990), equation (5) in Chari, Jones and Manuelli (1995), equation (2.4) in Ladron-de-Guevara et al. (1999) and equation (6) in Kosempel (2001, 2004).

[4]A formal version of Arrow's theorem is presented in the next section.

[5]It is assumed that the argument applies (Lebesgue) almost-everywhere regarding the time domain in which such functions are considered, and in an open and convex neighborhood (considering the state variable) of the candidate (s) for optimum.

Regarding the shopping-time literature, I concentrate the main analysis Cysne (2003). A solution to the problem of non-covexity found in Lucas (2000, section 5) follows the same general lines as those detailed here and is provided as a specific comment to that paper in Cysne (2004).

As it concerns the human-capital literature, I focus the analysis on Lucas (1988). The reason for concentrating on this paper is that its technology for accumulating human capital (equation (13) in Lucas (1988)) has been used by many other authors in the literature. This technology has actually been used before Lucas by Uzawa (1965)[6]. But it happens that Uzawa's results can be obtained as a special case of Lucas's modelling, when the utility is linear in consumption and there is not externality in production.

In the remaining of the paper, section 2 presents a formal version of Arrow's theorem. In section 3 I exemplify the use and usefulness of the theorem within the shopping-time literature and, in section 4, within the human-capital literature. Section 5 concludes.

2 Arrow's Theorem

Following Seierstad and Sydsater's (1987, p. 107 and page 236), Arrow's theorem, adapted to an infinite horizon, reads as follows[7]:

Theorem 1 *(Arrow's Sufficiency Theorem): Let* $(\bar{x}(t), \bar{u}(t))$ *(both continuously differentiable) be a pair that satisfies the conditions (2) and (3) below, in the problem of finding a piecewise-continuous control vector* $u(t)$ *and an associated continuously-differentiable state vector variable* $x(t)$*, with* $x(t)$ *belonging to a given open and convex set* $A \in \mathbb{R}^n$ *for each* $t \geq t_0$*, defined on the time interval* $[t_0, \infty]$ *, that maximizes:*

$$\int_{t_0}^{\infty} f_0(x(t), u(t), t)dt \tag{1}$$

subject to the differential equations:

$$\dot{x}_i(t) = f_i(x(t), u(t), t), \ \ i = 1, 2, ..., n \tag{2}$$

[6] As well as by Rosen (1967), but in another context.

[7] Seidseter and Sydersat (1977) argue (p. 370) that the first published demonstration of this theorem, which was presented in Arrow and Kurz (1970), is not satisfactory, and that a correct proof did not seem to be available in the literature till the publication of their work. This theorem was first mentioned in Arrow (1968).

and to the conditions

$$\begin{aligned} x_i^0(t_0) &= x_i^0 \ , \ i = 1, 2, ..., n & (3) \\ x_i(\infty) \ \textit{free}, \ i &= 1, ..., n \\ u(t) &\in \mathbb{U} \subset R^r. \end{aligned}$$

Suppose, in addition, that $\bar{x}(t)$ *belongs to (the open and convex set)* A *for all* $t \geq t_0$ *and that, given the Hamiltonian function:*

$$H(x(t), u(t), p(t), t) = f_0(x(t), u(t), t) + \sum_{i=1}^{n} p_i f_i(x, u, t)$$

there exists a piecewise continuously-differentiable function $p(t) = (p_1(t), ..., p_n(t))$ *defined on* $[t_0, \infty]$ *such that* $H(\bar{x}(t), \bar{u}(t), p(t), t)$ *exists and the following conditions are satisfied:*

$$\begin{aligned} H(\bar{x}(t), \bar{u}(t), p(t), t) &\geq H(\bar{x}(t), u(t), p(t), t), \ \textit{for all} \ u \in \mathbb{U}, \ \ t \in [t_0, \infty (4) \\ \dot{p}_i(t) &= -H_{x^i}(\bar{x}(t), \bar{u}(t), p(t), t), \qquad i = 1, ..., n \qquad (5) \\ \lim_{t \to \infty} p_i(x_i(t) - \bar{x}_i(t)) &= 0 \qquad\qquad i = 1, ..., n \qquad (6) \end{aligned}$$

$H^*(x, p(t), t) = \max_{u \in U} H(x, u, p, t)$ *exists and is a concave function of* x *for all* $t \geq t_0$*, then,* $(\bar{x}(t), \bar{u}(t))$ *solves problem (1)-(3) above.*

3 An Application in a Shopping-Time Model

In this section I apply Arrow's theorem to Cysne (2003).

Cysne (2003) considers an economy with n different assets performing monetary functions. Bonds (B) is the $(n+1)th$ asset. Bonds are used only as a store of value and pay the (endogenously determined) benchmark interest rate r. The monetary assets are represented by the $n-$dimensional vector $X = (X_1, X_2, ..., X_n)$, and their real quantities by the vector $x = (X_1/P, X_2/P, ..., X_n/P)$, P the price level. The real value of the sotck of bonds is $b = B/P$. Each asset $x_1, x_2, ..., x_n$ pays an interest rate $r_1, r_2, ..., r_n$. Relatively to the benchmark rate, paid by bonds, the vector of opportunity costs reads $u = (u_1, u_2, ..., u_n) = (r - r_1, r - r_2, ..., r - r_n)$.

With $g > 0$ denoting a discount factor and c consumption, households are assumed to maximize:

$$\int_0^\infty e^{-gt} \ U(c) dt \qquad (7)$$

The potential product (that available when the shopping time (s) is equal to zero) y is normalized to one. The household is endowed with one unit of time so that $y+s=1$. Make $r_R=(r_1-\pi, r_2-\pi, ..., r_n-\pi)$ and denote by π and h, respectively, the rate of inflation and the lump-sum transfers from households to the government. When maximizing (7), households face the budget constraint:

$$\dot{b}+\sum_{i=1}^{n}\dot{x}_i=1-(c+s)-h+(r-\pi)\ b+\langle r_R, x\rangle \tag{8}$$

and the transacting-technology constraint:

$$c=G(x)s \tag{9}$$

The monetary aggregator function $G(x)$ is differentiable, increasing in each one of the x variables, first degree homogeneous, and concave in x.

As in Lucas (2000), the utility function is assumed to be given by:

$$\begin{aligned} U(c) &= c^{1-\sigma}/(1-\sigma),\ \sigma\neq 1, \sigma>0 \\ U(c) &= \ln c \text{ (case } \sigma=1) \end{aligned} \tag{10}$$

Below, we shall call σ the coefficient relative risk aversion[8].

The Hamiltonian for the problem reads:

$$H(s, G(x), b, \lambda)=U(G(x)s)+\lambda(1-(G(x)+1)s-h+(r-\pi)b+\sum_{j=1}^{n}(r_j-\pi)x_j) \tag{11}$$

In order to apply Arrow's theorem, consider s as the only control variable, and b and x as the state variables[9]. The above Hamiltonian clearly is not concave in these variables because of the term $(G(x)+1)s$. The maximization of (11) with respect to s leads (in any case) to:

$$s=\frac{1}{G(x)}(\frac{G(x)+1}{G(x)}\lambda)^{-1/\sigma} \tag{12}$$

[8] Since there is no uncertainty in the model, σ should actually be called "the inverse of the elasticity of intertemporal substitution".

[9] Working with $a=b+\sum_{j=1}^{n}x_j$ as the only state variable (and s, and the x_j's as control variables) leads to the same first-order conditions as when one formulates the problem regarding only s as a control variable and the x_j's and b as state variables. Such first-order conditions obey $-\dot{\lambda}(t)+g\lambda(t)=H_{x_j}$ and $-\dot{\lambda}(t)+g\lambda(t)=H_b$ which is the property required from the state variables in the application of the theorem.

Substituting the expression of s into the Hamiltonian (11) leads to the maximized Hamiltonian:

$$H^*(G(x),b,\lambda) = \frac{\sigma}{1-\sigma}\left(\frac{G(x)}{\lambda(1+G(x))}\right)^{(1-\sigma)/\sigma} + \lambda(1-h+(r-\pi)b+\sum_{j=1}^{n}(r_j-\pi)x_j), \quad (\sigma \# 1)$$

$$H^*(G(x),b,\lambda) = \log\frac{G(x)}{\lambda(1+G(x))} + \lambda(1-1/\lambda-h-(r-\pi)b+\sum_{j=1}^{n}(r_j-\pi)x_j)), \quad (\sigma = 1)$$

The next step in the application of the theorem is showing that the maximized Hamiltonian is concave with respect to the state variables x and b. Since the term in b is linear, the only variables we have to care about are those in the vector x. More precisely, those which are not in the linear term $\sum_{j=1}^{n}(r_j-\pi)x_j$. The Hamiltonian is trivially concave in the case $\sigma = 1$ since $G(x)$ is concave and increasing in x and, given λ ($\lambda = \frac{U'(G(x)s)G(x)}{1+G(x)} \geq 0$), and taking $G(x)$ as a variable, $\log\frac{G(x)}{\lambda(1+G(x))}$ is a composite function of two monotone increasing concave functions. When $\sigma \neq 1$, note that the term $\frac{\sigma}{1-\sigma}(\frac{G(x)}{\lambda(1+G(x))})^{(1-\sigma)/\sigma}$ in the maximized Hamiltonian is concave in x (by the same result that composite functions of increasing and concave functions are concave) provided that:

$$\sigma \geq \frac{1}{2} \tag{13}$$

The extension of this reasoning to Cysne, Monteiro and Maldonado (2004) is straightfoward. The intuition[10] for this result is presented in Figures 1 and 2 below.

(Please Insert Figures 1 and 2 here)

Figure 1 presents the case in which the coefficient of risk aversion is high enough. The feasible region of maximization is determined by the level curve of the term multiplying λ in (11). Even though this equation (through it's isoquant) determines a non-convex feasible region in the $(G(x), s)$ plane (the shadowed region in the figures), if the curvature of the utility function is high enough the non-convexity poses no problem.

Figure 2 presents the problematic case, in which the first-order conditions (with equality) fail to characterize the optimum. This happens when the coefficient of risk aversion σ is not high enough.

[10] Note that condition (13) makes $U(G(x)s)$ strictly concave in both G (by these means, also in x) and s in the original problem, but not the original Hamiltonian (11). Therefore, Mangasarian's (1966) sufficient conditions cannot be used in this case as well.

4 An Application in a Human-Capital Model

In this section I will repeat the procedure of the last section, taking one paper in the human-capital literature and showing how it can benefit from the application of Arrow's theorem. For the reasons detailed in section 1, Lucas (1988) is a natural choice. In this paper preferences over consumption streams are (I omit the argument t of the functions in order to simplify the notation):

$$\int_0^\infty e^{-\rho t}\frac{N}{1-\sigma}(c^{1-\sigma}-1),\ \sigma>0$$

and human capital (h) accumulates according to:

$$\dot{h}=h(1-u)$$

Above, c (per-capita consumption) and u (the fraction of non-leisure time devoted to production) are control variables in the optimum path chosen by the representative consumer. N is the total number of workers and uNh is the effective workforce used in the production of the consumption good.

With K standing for the level of physical capital, the technology of goods production is:

$$Nc+\dot{K}=AK^\beta(u\,\mathrm{N}h)^{1-\beta}h^\gamma,\quad A>0,\quad 0<\beta<1,\quad \gamma\geq 0 \tag{14}$$

The last term in the second member of equation (14), h^γ, stands for the externality of the level of human capital in the production of the consumption good. In the problem solved by the representative consumer (as opposed to that solved by a social planner), this term is taken as given.

The Hamiltonian in then given by (Lucas, 1988, p. 20):

$$\begin{aligned} H(K,h,\theta_1,\theta_2,c,u) \;=\; & \frac{N}{1-\sigma}(c^{1-\sigma}-1)+\theta_1\left[AK^\beta(u\,\mathrm{N}h)^{1-\beta}h^\gamma-Nc\right] \\ & +\theta_2\left[\delta h(1-u)\right] \end{aligned} \tag{15}$$

θ_1 and θ_2 are multiplier functions that give the marginal value of the state variables K and h, respectively, discounted back to time zero. Both θ_1 and θ_2, therefore, are nonnegative.

This Hamiltonian is clearly nonconcave in the control and state variables due to the term $h(1-u)$. Denoting by H_x the derivative of H with respect to (the generic) variable x:

$$H_c=Nc^{-\sigma}-\theta_1N$$

$$H_u = \theta_1 A K^{\beta}(\mathrm{N}h)^{1-\beta}(1-\beta)h^{\gamma}u^{-\beta} - \theta_2\delta h$$

It also follows form the above equations that $\mathrm{H}_{cc} = 0 < 0$, $\mathrm{H}_{\mathrm{uu}} < 0$ and $\mathrm{H}_{uc} = 0$. Therefore, the Hamiltonian is strictly concave in (c, u). The unique optimum values of these control variables can be found by making $\mathrm{H}_c = H_u = 0$, in which case:

$$c = \theta_1^{\frac{-1}{\sigma}} \tag{16}$$

$$u = (\frac{\theta_2\delta}{\theta_1 A\,\mathrm{N}^{1-\beta}(1-\beta)})^{-\frac{1}{\beta}} K h^{\frac{\gamma-\beta}{\beta}} \tag{17}$$

Substitute (16) and (17) in (15). The optimized (with respect to the control variables) Hamiltonian reads:

$$\begin{aligned} H^*(K, h, \theta_1, \theta_2) &= \frac{N}{1-\sigma}(\theta_1^{\frac{\sigma-1}{\sigma}} - 1) + \theta_1 K A\,\mathrm{N}^{1-\beta}(\frac{\theta_2\delta}{\theta_1 A\,\mathrm{N}^{1-\beta}(1-\beta)})^{\frac{-1+\beta}{\beta}} h^{\frac{\gamma}{\beta}} \\ -\theta_1^{\frac{\sigma-1}{\sigma}} N &\quad + \theta_2\delta\left[h - (\frac{\theta_2\delta}{\theta_1 A\,\mathrm{N}^{1-\beta}(1-\beta)})^{-1/\beta} h^{\frac{\gamma}{\beta}} K\right] \end{aligned}$$

Since $\gamma \geq 0$, the optimized Hamiltonian is concave in the state variable K and h (though not strictly concave) only for $\gamma = 0$.

We conclude that, when there is no externality in the production of the consumption good due to the human-capital accumulation, the first-order conditions derived in the problem do represent a (not-necessarily-unique) optimum. Note that having $\gamma > 0$ is not so important in the theory developed by Lucas (1988), since it predicts sustained growth whether or not the external effect is present. The case $\gamma = 0$ (with $\sigma = 1$, linear utility) corresponds to Lucas's version of Uzawa's (1965) paper.

The case $\gamma > 0$ is not covered by Arrow's theorem. Characterizing the optimum in this case requires other techniques.

5 Conclusion

In this work I have chosen two papers, respectively, in the shopping-time and in the human-capital literature, in which the usual Mangasarian's sufficiency conditions for optimality in dynamic programming are not met. In such cases, Pontryagin's (1962) Maximum Principle cannot tell us if a point satisfying the first-order conditions represents an optimum or not. Next, I have shown, in each case, that optimality can be characterized by means of a simple aplication of Arrow's (1968) sufficiency theorem.

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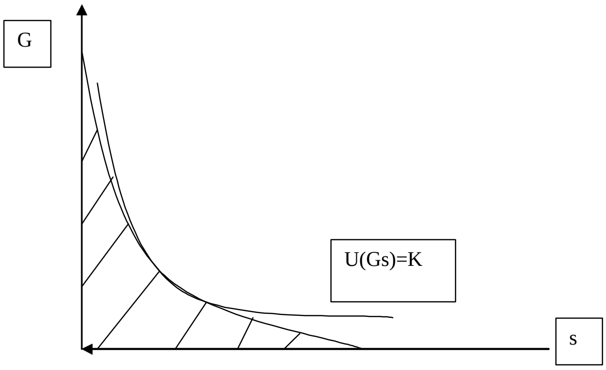

Figure 1: Non-Problematic Case - Coefficient of Risk Aversion High Enough

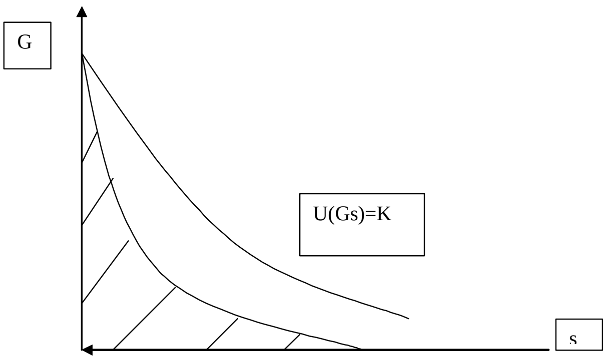

Figure 2: Problematic Case - Coefficient of Risk Aversion Not High Enough

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